GROUNDWATER MANAGEMENT: AN OVERVIEW OF HYDRO-GEOLOGY, ECONOMIC VALUES, AND PRINCIPLES OF MANAGEMENT

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Contents

1. Introduction

The issues surrounding groundwater, its instrumental uses and ecological functions, and the management thereof typify the interaction of humankind with the resources that sustain it. Perhaps most importantly groundwater is an immensely important resource in that it is estimated to represent 94% of the planet's freshwater resources. It is therefore inevitable that groundwater has become socially and economically important for a variety of reasons. Firstly, it is frequently a cheap source of water, providing costless water storage that economizes on evaporation, whilst being accessible above ground without complicated transfer schemes. Secondly, groundwater is a key input in all of the conventional economic sectors: industry, agriculture, tourism, households etc., and in many countries groundwater represents the source of more than half of annual water consumption. This is especially so in arid countries and many small islands in which perennial surface water is scarce. In such regions groundwater can act both as a substitute for surface water, facilitating economic development where previously it would be absent, and a complement to surface water, acting as an insurance policy or buffer against climatic uncertainty and drought. Groundwater provides many of these essential services wherever it is found, in developed and less developed countries, arid and humid alike.

Although important from this purely economic viewpoint, like many natural resources, groundwater is an intrinsic part of wider ecological processes. It is frequently merely a component of the hydrological cycle and from a management perspective can seldom be considered in isolation. In this regard a common phenomenon is that groundwater and surface water are conjoined, which means that the effects of groundwater abstraction will extend beyond individual users to the functions and processes sustained by surface water. These functions and processes not only include the conventional economic sectors but also the ecological functions such as the maintenance of riverine systems, their base flows, associated flora and fauna, and wetland ecosystems. Furthermore groundwater is a dynamic resource in that changes in the size and quality of groundwater stocks, induced by natural causes or human intervention, frequently have long lasting and occasionally irreversible effects. For example, land subsidence and aquifer collapse can be common yet often unpredictable and irreversible consequences of groundwater abstraction. Where quality is concerned, seawater intrusion represents another potentially irreversible change. Hence, the effects of abstractions upon groundwater reserves and associated ecological functions can be long lasting and almost always carry an element of unpredictability.

In addition, groundwater aquifers differ considerably in their geological and hydrological characteristics, which means that there is no 'one size fits all' model with which to analyze them. From the perspective of sustainable use perhaps one of the most important distinctions relates to the presence or absence of natural recharge. The potential for recycling withstanding, in the former case groundwater can be seen as a renewable resource like forests or fisheries, in the latter it can be seen as an exhaustible resource like oil or coal. Along with the issue of conjointness, each scenario will require a different management approach.

In light of the above characteristics, the planning and management of groundwater is a challenging and ever-evolving task. This challenge is compounded by the socio-economic context: the nature of human interaction and the legal and institutional backdrop, which provide the rules of engagement. It is widely argued that the inefficient use of groundwater, often reflected by premature exhaustion, is the result of weak or perverse property rights systems which make groundwater an ‘open access’ or a ‘common property’ resource. One extreme example is when groundwater is shared by two or more sovereign states: it is a trans-boundary resource. For example, the Qa Disi aquifer is shared between Jordan and Saudi Arabia. In the absence of cooperation, each country competes for the resource and mining is quickened as a result. A similar effect occurs between individuals sharing the same aquifer under open access. Again, the assignment of property rights and the details thereof are important determinants of groundwater use and the benefits to society that it affords.

Clearly there are a number of issues concerning groundwater, which indicate the need for intervention if such resources are to be used efficiently, in a sustainable manner and distributed equally across potential users. Indeed, whether or not groundwater use should be regulated, and the manner in which this is done represents one of the most important issues in the arena of water resource management.

2. Groundwater: Hydro-Geology

Groundwater systems are composed of saturated rocks and/or sediment in a variety of geological formations. In general if such a formation can produce useable quantities of water it is known as an aquifer. The geological variation in aquifers means that they vary in their physical characteristics, such as whether or not they are replenished or recharged by surface water or precipitation and hence the extent to which they can be seen as renewable or exhaustible resources. In addition, the response of groundwater stocks to abstractions is determined by the geological structure. Therefore in order to understand the dynamics of a particular aquifer, it is important to determine the nature of the particular hydrological and geological environment. The important distinctions between and characteristics of aquifers are outlined in brief below.

2.1. Unconfined and Confined Aquifers

Broadly speaking unconfined aquifers are subject to recharge by precipitation and/or surface water, which infiltrates vertically downwards through the overlying ground structure. The upper threshold of an unconfined aquifer is known as the water table, and water contained therein can be considered renewable. A *perched* aquifer represents a special case of an unconfined aquifer and can be thought of as an impermeable shelf in an otherwise permeable ground upon which water infiltrating from above is held for a period of time determined by the permeability of the surrounding ground.

Confined aquifers on the other hand, lie beneath less porous layers of rock, or aquitards, which either preclude recharge altogether or limit recharge to lateral underground flows from recharge zones where the aquitard is absent. Confined aquifers which are not subject to recharge can contain water which was deposited many thousands or even millions of years ago; so called fossil water, and water contained therein can be considered an exhaustible resource.

The distinction between confined and unconfined aquifers often lies in the pressure of the groundwater. Artesian wells such as the great artesian basins of east-central Australia and the south east Kalahari aquifer in Namibia contain water which, once tapped, is under sufficient pressure to reach ground level or higher. Such flows emanate from confined aquifers, which are under more than the atmospheric pressure associated with unconfined aquifers. However, in reality the division between confined and unconfined aquifers is less distinct, and in general both form component parts of a single hydrological system.

2.2. Conjoined Surface and Groundwater

A further distinction also important, particularly when considering water resource management, is the extent to which aquifers are conjoined to other surface water bodies such as lakes or rivers. Tributary aquifers are those located adjacent to and beneath rivers and other such watercourses. The behavior of these unconfined aquifers is directly linked to that of the watercourse and vice versa. The South Platte River in Colorado, US provides an example of surface water conjoined to an alluvial aquifer. The aquifer is recharged predominantly by the river, whilst abstractions from the aquifer affect the surface water flow. Furthermore, water stored in aquifers may also represent the source of springs and as such any economic use or ecological process linked to these springs will also be linked to the stock, rather than the flow, of groundwater.

2.3. Composition and Physical Characteristics

Aquifers vary in their geological composition and hence physical properties, most important of which are storage capacity and the subsurface flows of groundwater e.g. in response to pumping. Some important characteristics are as follows:

- **Porosity**: measures the percentage of a given rock made up by voids or holes (interstices) in which water can be stored. Such voids can represent the nature of the aquifer medium e.g. pores in limestone or inter-granular spaces in sandy aquifers, or from secondary effects such as rock movements or weathering.
- **Storativity**: also known as the coefficient of storage, represents the volume of water that can be extracted from a given surface area of an aquifer per unit change in depth (or head).
- **Transmissivity**: measures the extent to which a reduction in groundwater level due to pumping at a particular point is transmitted to the rest of the aquifer. I.e. the extent to which the water level goes down locally or uniformly across the entire surface area of the aquifer. Where transmissivity is low the water level only recedes locally and in extreme cases giving rise to cones of depression. Where transmissivity is high, local pumping affects the water level across the whole aquifer.

Aquifers also differ in the extent to which they are subject to irreversible changes as a result of abstractions. For example, coastal aquifers are frequently affected by saline/seawater intrusion. This has occurred for example in the Kiti aquifer in Cyprus and the Hermosillo aquifer in Mexico. Once this intrusion has occurred it is either irreversible or reversed at significant cost through the injection of recycled or semipurified water: artificial injection. Similarly, the collapse of aquifers due to abstraction, and the associated loss of storage, is a common and irreversible occurrence. In central parts of Arizona for example, land surfaces have subsided by up to 9m over the past 20 years as a result of abstractions.

3. The Value of Groundwater

Groundwater is a valuable resource for a number of reasons. When abstracted groundwater acts as a current input into the conventional economic sectors of industry, agriculture and households, it represents the extractive value of groundwater. When left in the ground, as well as supporting many ecosystem functions as an important component of the wider hydrological and ecological system, it leaves the option of abstraction in the future. Thus, in addition to the direct use or extractive values, groundwater also has an *in situ* value, i.e. a value associated both with saving for the future and maintaining ecosystem functions. In determining the pattern of use, which best fulfils societal objectives it is the tension between extractive and *in situ* values which best describes the trade-offs faced by the resource manager. Determining the trade-off requires the knowledge of all of the economic values associated with groundwater: i.e. the Total Economic Value (TEV).

TEV is defined to include both direct/extractive use and non-use values, i.e. those values generally associated with environmental goods. Whilst the extractive values are well represented and valued by the conventional economic sectors, there are a number of *in situ* values, which require special attention. *In situ* values include:

- **Buffer values**: The insurance value associated with the buffer that stocks of groundwater provide when used conjunctively with uncertain surface water.
- **Subsidence avoidance**: Subsidence is one of the consequences of groundwater abstraction and as such subsidence avoidance is an *in situ* value.
- **Ecological service**: Groundwater reserves are often the source of river base flow, springs, and have other ecosystem linkages. Another ecosystem service is water purification. Maintaining groundwater stocks maintains any associated ecological services.
- **Recreational services**: The maintenance of surface water flows means that any associated recreational and other services are preserved.
- **Future values**: In general, the option to use groundwater in the future is defined as an *in situ* value

There are a variety of techniques available to make these values commensurate with one another and therefore to allow trade-offs to be made between them in the process of maximizing that value. Economists have generally used monetary values as a yardstick and these values have been estimating the willingness to pay if individuals for the various aspects of groundwater value.

4. Groundwater Scarcity: Demand and Supply Side Factors

Over the past 40 years a number of factors have conspired to reduce both the quantity and quality of groundwater resources to critical levels in many parts of the world.

Groundwater overdraft, defined as using more groundwater than is naturally replenished, has occurred in countries such as Jordan, Mexico, the United States, Namibia and Yemen. The prevalence of these overdrafts is of particular importance in arid countries where groundwater is the predominant source of water such as Jordan, Namibia and Yemen. With the exhaustion of groundwater stocks expensive investments in long distance surface water transfers or desalination are frequently seen as the solution. Clearly these investments should be assessed in light of alternative management strategies for groundwater. Similarly, groundwater quality issues are of particular moment in many countries. One of the most frequently cited examples is that of Bangladesh, where groundwater is polluted by naturally occurring arsenic, causing considerable health problems to poor rural communities. Furthermore, in many areas groundwater stocks have been polluted by agricultural or industrial wastes and residues. This state of affairs has sparked renewed analysis of the causal factors of groundwater depletion and placed the principles of groundwater management under close scrutiny.

The causal factors are frequently categorized as either supply or demand side. On the supply side several factors are often credited with encouraging more intensive and extensive exploitation of groundwater. For example, improvements in pumping technology such as more powerful pumping equipment and submersible pumps naturally make it feasible to tap deeper reserves. Similarly, reductions in the financial cost: investment, operations and maintenance costs, have provided cheap access to groundwater. Naturally government policies concerning the inputs to groundwater pumping, such as the subsidized fuel provided to rural areas of Namibia and subsidized electricity in areas of India and Pakistan, although implemented with the objectives such as rural development and poverty alleviation in mind, have also accelerated the degradation, mining and occasionally the exhaustion of groundwater resources. In combination these supply side factors have allowed existing wells to be exploited more deeply whilst opening the door to further exploitation from new and lower cost wells.

On the demand side population growth puts pressure upon groundwater resources. The demand side pressure that population growth can impose upon groundwater resources is not exclusive to the less developed countries with which levels of national annual population growth of up to 3% are frequently observed. Indeed most countries have experienced localized population growth as a result of rural-urban migration, and many countries experience the seasonal population explosions associated with tourism. Nowhere is this more apparent than in the coastal resorts of the Mediterranean where the exploitation of coastal aquifers is often complete either with regard to quantity or quality.

Furthermore, in many countries macro economic factors such as economic growth have increased the demands for all water resources, particularly groundwater. One way to think about the effect of economic growth is as follows: income growth leads to increased demand for goods which embody groundwater resources; high value foodstuffs, manufactures, electricity, tourism etc. As a result private sector activities and often macro-economic policies reorient to reflect these demands. Irrigated agriculture, which represents perhaps the largest user of groundwater resources in many parts of the world, provides a good example of this. All year demand for seasonal fruits and vegetables combined with access to cheap groundwater resources has provided the backdrop for agricultural policies to promote export lead growth through high value irrigated foodstuffs. The promotion of tourism is another pervasive demand side factor in many island economies of the Mediterranean and Caribbean for example. Similarly groundwater is an essential input to manufacturing and industry, which for a long time and more generally were the main engines of economic growth. On top of this, it is frequently observed that as incomes rise, per capita consumption of water for household and domestic purposes rises in line with the purchase of consumer durables such as dishwashers, swimming pools, large houses with gardens etc.

In many of the above cases, the underlying factor and one of the most important demand side issues in groundwater management is that of water pricing. It is frequently the case that the incidence of groundwater overdraft arises in tandem with policies to subsidize water to household, agricultural and industrial sectors. That the demand and price of goods move in opposite directions is as true for water as it is for most normal economic goods. Therefore pricing policies represent another important determinant of groundwater use. In addition to micro level policies such as water pricing, macro economic and sectoral policies can also conspire to increase the pressure upon resources. For example, the availability of cheap or subsidized groundwater combined with perverse agricultural policies, such as national food self-sufficiency in arid water scarce countries, can lead to groundwater depletion for the purpose of growing low value goods. In this way groundwater is mined while providing very little contribution to social welfare.

Clearly, population growth, migration, economic growth and other supply and demand side factors reflect wider socio-economic, political and cultural trends making the causes of groundwater scarcity apparently complicated and difficult to disentangle. However, in order to determine whether or not the observed pattern of groundwater use is beneficial to society or represents some a management failure from the perspective of societal welfare it is important define some principles of groundwater management which can act as benchmarks for good practice.

5. Principles of Groundwater Management

Natural resource economics is perhaps the most relevant discipline from which to derive these benchmarks as it has well defined measures of societal welfare which incorporate natural resource dynamics and allow comparisons between many alternative objectives. The most important of these principles are efficiency, sustainability and equity.

5.1. Economic Efficiency (and Inefficiency)

Economic efficiency in resource use is achieved when no rearrangement of resources between individuals or across time can improve the welfare of society. This general definition implies two aspects to economic efficiency: static efficiency (efficient allocation of resources between potential users) and dynamic efficiency (efficient allocation over time). Both aspects can be brought to bear upon the management of groundwater resources and used as a benchmark for management practices.

Groundwater aquifers can be broadly categorized as renewable or non-renewable and the nature of efficient use differs in each case. In both cases however, groundwater represents a stock of resources as distinct from a flow such as a river. As such groundwater can be considered a dynamic resource because changes in the stock that occur today, as a result of recharge or abstraction by humans, have inter-temporal consequences. Hence, the concept of dynamic efficiency is particularly relevant to groundwater. Put loosely, the efficient use of non-renewable groundwater will reflect the long-run since with continued use it will eventually be either physically or economically exhausted i.e. abstraction will become too expensive. On the other hand, renewable groundwater has the potential to be used for all time if abstractions remain equal to recharge. Thus the efficient use of renewable resources will consider the balance between abstractions and recharge (stocks and flows). The management questions that remain concern the date at which aquifers should be exhausted, the path of abstraction over time, whether or not it is efficient to use groundwater sustainably and if so the level of the aquifer stock at which this use is maintained. However, as described above many aquifers are conjoined with surface water and/or are pivotal in maintaining wider ecological functions. Hence it is generally insufficient to consider groundwater in isolation since these wider effects are also important in determining efficient management. This section describes the efficient use of groundwater that would be chosen by a government wishing to maximize social welfare over time and the inefficiencies that arise when decision-making is placed in the hands of individual groundwater users.

5.1.1. Efficient Groundwater Management

The management of groundwater resources is deemed economically efficient when groundwater abstraction is chosen such that its allocation over time (time-path), exhaustion date, the stock and the impacts on conjoined resources and other third parties generate the maximum welfare to society. In other words economic efficiency is a question of choosing the temporal pattern of abstraction, which maximizes the TEV of groundwater. This amounts to maximizing the present value of the difference between social benefits and social costs of abstraction.

The economic value or social benefits of groundwater are derived from consumption over time by both conventional productive sectors of the economy; households, manufacturing, agricultural, recreational etc., and non-conventional sectors such as the environment. For example, in Colorado groundwater is pumped in order to augment surface water, which also maintains environmental flows. The social costs of abstraction are more complicated however, reflecting the dynamic nature of the resource, and can be usefully categorized as follows:

- **Contemporary Costs**: Contemporary costs are those incurred as pumping occurs. These include the costs of abstraction: the operations and maintenance of pumps for example.
- **Inter-temporal Costs**: Inter-temporal costs refer to the change in the level of the groundwater stock, which in turn affects the availability of groundwater for any of the aforementioned uses in the future. This includes the loss of amenity associated with the groundwater stocks. For example, springs that emerge from

the Edwards Aquifer in Texas US support ecosystems containing many varieties of endangered fish. Inter-temporal costs may also include the value of groundwater as an insurance policy against climatic uncertainty or uncertain surface water flows: the so-called 'buffer value' that have been estimated in agricultural communities in many arid and semi arid environments.

- **Quality related costs**: Lastly there are quality related costs. These costs may be contemporary or inter-temporal and may arise as a result of the pumping itself or as a result of the use to which the groundwater is put. Seawater intrusion is an example of the former whilst groundwater pollution as a result of the infiltration of agricultural herbicide residues is an example of the latter. Both limit the contemporary and future uses to which groundwater can be put.

In short, in addition to the contemporary costs that current users face, abstraction today may preclude abstraction tomorrow as a result of physical or economic exhaustion. E.g., abstraction today may cause irreversible changes in the structure of the aquifer (collapse or compaction, quality reduction), which may make the abstraction of water impossible or too costly tomorrow. Inter-temporal costs reflect the dynamic nature of the groundwater and the value of leaving the resource in the ground. The extent of these costs will be determined as much by the properties of the aquifer as by the abstraction decisions and the demand for water. It is common to label those costs that are not directly faced by those who abstract groundwater as the **user cost** or **scarcity rent** since these values represent the properly reflect the value of the scarce resource in the ground and the economic impact of abstraction.

Determining the efficient use of groundwater is clearly a multidisciplinary task and informationally intensive. Firstly, hydrological models are required to characterize the nature and behavior of the aquifer, e.g. the resource stock, storativity, transmissivity etc. Secondly, the socio-economic environment must be described. This requires identifying and placing a commensurate economic value upon all groundwater and conjoined uses and functions. Static efficiency requires allocating groundwater to the highest value uses at a particular point in time. In order to determine a dynamically efficient time path of groundwater use requires combining economic and hydrological models and defining the interaction between the uses/users and the resource. It is then possible to solve for the allocation that maximizes present value of the difference between social benefits and social costs over a predetermined planning horizon. This is usually performed by dynamic optimal control methods.

There are several parameters of interest in determining the efficient allocation of groundwater. Perhaps the most important is the users' responsiveness to changes in the price of groundwater, the so-called price elasticity of demand (PED). This will determine the way in which individual demands for water will change over time in response to the increased pumping costs associated with groundwater depletion. Similarly, it will be important to understand how the demand for water changes over time with incomes. The natural corollary is the need for projections for population and economic growth.

Although modeling these above and below ground aspects and the interface between them is fraught with uncertainty, there have been great advances in hydro-geological modeling, economic modeling and economic valuation techniques. These advances have enabled comprehensive hydro-economic modeling and the determination of efficient abstraction plans. Examples of where dynamic optimal control of aquifers has been undertaken include Ogallala Aquifer, Colorado, the Kiti Aquifer, Cyprus, the South East Kalahari Artesian Aquifer in Namibia etc. Environmental values have been estimated for many aspects of watersheds, including the various values associated with groundwater.

5.1.2. Efficiency with Water Transfers and Backstop Technologies

The previous analysis has been assuming almost implicitly that groundwater users are those who occupy the overlying land. Another issue pertinent to the question of efficiency is whether or not the incumbent property rights holders to groundwater represent the highest value to society. This brings to light the potential for the transfer of water outside of the land overlying the aquifer, or even to an entirely separate river basin: an inter-basin transfer. The government or groundwater manager should be aware of such latent societal values in determining the efficient use of groundwater. The issues surrounding the property rights to groundwater and the extent to which they may be transferable to higher value uses either *in situ* or elsewhere is discussed further below.

Furthermore, the efficient use of groundwater should be not determined in isolation from alternative sources of water. For example, coastal aquifers should not be used if the costs of doing so are greater than for desalination. In Cyprus for example, groundwater augments the supply from desalination, and groundwater is managed such that the costs of abstraction do not rise beyond that of desalination. The existence of a backstop technology, e.g. water transferred from another river basin, also determines the efficient use of groundwater.

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Zilberman D, Zeitouni N and Becker N (2001). 'Issues in the Economics of Water Resource'. Ch2 in The international Yearbook of Environmental and Resource Economics (2000/2001). Tietenberg T and Folmer H (eds). [This article provides a useful summary of the important issues in the economics of water resources up to the year 2000. Groundwater, surface water and different economic sectors are included in the summary.]

Groundwater User Associations websites:

Websites for some of the US groundwater districts and river basin authorities can be found at the following addresses:

www.texasgroundwater.org

www.gmda.nrc.state.ne.us

www.angelfire.com/tx/gcuwd

Biographical Sketches

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Ben Groom. MSc, BA. Ben Groom is a research fellow at the Centre for Social and Economic Research for the Global Environment (CSERGE) and teaching assistant at the Department of Economics, University College London. He is currently in the final year of his PhD thesis entitled 'Essays in Environmental and Natural Resource Economics'. This research concerns several aspects of economics including water resource economics, groundwater management, discounting and long-run discounting for cost-benefit analysis, biodiversity, biotechnology and intellectual property rights. Prior to undertaking his PhD he has worked as a water resource economist for the Government of Namibia in the Department of Water Affairs, Ministry of Agriculture, Water and Rural Development as part of the Overseas Development Institute (ODI) Fellowship scheme. In this role he involved in formulating policy as part of the World Bank Namibian Water Resources Management Review (NWRMR). This review covered policy concerns in a wide spectrum of water resource management issues including groundwater management, trans-boundary negotiations for water resources, institutional issues, water pricing and rural and urban water demand management. This experience was brought to bear upon the EU funded Cyprus Integrated Water Management Project, for which he was assistant coordinator and research assistant. He has also worked for the Natal Parks Board in South Africa, as a consultant to the World Bank in Kosovo in the area of public expenditure management, and the International Institute for Environment and Development. (IIED).